

"Experiments in Micro-metallurgy:—Effects of Strain. Preliminary Notice." By JAMES A. EWING, F.R.S., and WALTER ROSENHAIN, 1851 Exhibition Research Scholar, Melbourne University. Received and Read March 16, 1899.

[PLATES 1—5.]

Much information has been obtained regarding the structure of metals by the methods of microscopic examination initiated by Sorby and successfully pursued by Andrews, Arnold, Charpy, Martens, Osmond, Roberts-Austen, Stead, and others. When a highly polished surface of metal is lightly etched and examined under the microscope, it reveals a structure which shows that the metal is made up in general of irregularly shaped grains with well defined bounding surfaces. The exposed face of each grain has been found to consist of a multitude of crystal facets with a definite orientation. Seen under oblique illumination, these facets exhibit themselves by reflecting the light in a uniform manner over each single grain, but in very various manners over different grains, and, by changing the angle of incidence of the light, one or another grain is made to flash out comparatively brightly over its whole exposed surface, while others become dark.

It is also well known that the grains are deformed when the metal is subjected to such processes as cold hammering, or cold rolling, or wire-drawing. On polishing and etching a piece strained in any such way, the grains are found to be on the whole longer in the direction in which the metal is extended than in other directions. But on heating the metal sufficiently a re-formation of structure occurs, and the grains are found to have again assumed forms in which there is no direction of predominating length. In iron this recrystallisation occurs at a red heat. It is also known that prolonged exposure of iron to a temperature of about 700° C. tends to produce a larger granular structure than is found if the metal is somewhat quickly cooled from a higher temperature.

The grains appear to be produced by crystallisation proceeding, more or less simultaneously, from as many centres or nuclei as there are grains, and the irregular more or less polygonal boundaries which are seen on a polished and etched surface result from the meeting of these crystal growths. The grains are, in fact, crystals, except that each of their bounding surfaces is casually determined by the meeting of one growth with another. This is, we believe, the view usually accepted by metallurgists;* but there is considerable difference of opinion as to the part played by foreign matter in possibly contributing to form a cement at the intergranular junctions.

* See especially two papers by Mr. J. E. Stead ('Jour. Iron and Steel Inst.', 1898).



The experiments, of which this is a preliminary account, have been directed to examine the behaviour of the crystalline grains when the metal is subjected to strain.

For this purpose we have watched a polished surface under the microscope while the metal was gradually extended until it broke. By arranging a small straining machine on the stage of the microscope, we have been able to keep under continuous observation a particular group of crystalline grains while the piece was being stretched, and have obtained series of photographs showing the same group at various stages in the process. Strips of annealed sheet iron, sheet copper, and other metals have been examined in this way. We have also observed the effects of strain on the polished surfaces of bars in a 50-ton testing machine by means of a microscope hung from the bar itself, and have further observed the effects of compression and of torsion.

When a piece of iron or other metal exhibiting the usual granular structure is stretched beyond its elastic limit a remarkable change occurs in the appearance of the polished and etched surface, as seen by the usual method of "vertical" illumination. A number of sharp black lines appear on the faces of the crystalline grains : at first they appear on a few grains only, and as the straining is continued they appear on more and more grains. On each grain they are more or less straight and parallel, but their directions are different on different grains. At first, just as the yield-point of the material is passed, the few lines which can be seen are for the most part transverse to the direction of the pull. As the stretch becomes greater oblique systems of lines on other grains come into view.

The photograph, fig. 1 (Plate 1), taken from a strip of transformer plate (rolled from Swedish iron and annealed after rolling), gives a characteristic view of these lines as they appear after a moderate amount of permanent stretching, but long before the iron has reached its breaking limit.

The appearance of each grain is so like that of a crevassed glacier, that these dark lines might readily be taken for cracks. Against this, however, was the consideration that an over-strained piece of iron recovers its original elasticity after a period of rest, though, as we found, the dark lines did not disappear when recovery took place, and further that sharp lines of the same nature were not seen on the surface of metal which was polished and etched after straining.

The real character of the lines is apparent when the crystalline constitution of each grain is considered. They are not cracks, but *slips* along planes of cleavage or gliding planes.

Fig. 2 is intended to represent a section through the upper part of two contiguous surface grains, having cleavage or gliding planes as indicated by the cross-hatching, AB being a portion of the polished surface. When the metal is pulled beyond its elastic limit, in the

direction of the arrows, yielding takes place by finite amounts of slips occurring at a limited number of places in the manner shown at *a*, *b*, *c*, *d*, *e* (fig. 3). This slip exposes short portions of inclined surfaces, and when viewed under normally incident light, these surfaces appear black because they return no light to the microscope. They are consequently seen as dark lines or narrow bands, extending over the polished surface in directions which depend on the intersection of the polished surface with the surfaces of slip.

We have proved the correctness of this view by examining these bands under oblique light. When the light is incident at only a small angle to the polished surface, the surface appears for the most part dark; but here and there a system of the parallel bands shines out brilliantly, in consequence of the short cleavage or gliding surfaces which constitute the bands having the proper inclination for reflecting the light into the microscope. Fig. 4 is the photograph of a strained piece of Swedish iron illuminated in this way. The magnification is 280 diameters. The groups of parallel bright bands which appear in the photograph may readily be observed under the microscope to be exactly coincident with the black bands seen under vertical illumination; and by changing the angle of incidence of the oblique light, the same bands may be made to appear dark on a faintly luminous ground. Rotation of the stage to which the strained specimen is fixed makes the bands on one or another of the grains flash out successively, with kaleidoscopic effect. In what follows we shall speak of these lines as slip bands. Fig. 1, through a mixed illumination, shows some of the slip bands bright and some dark.

Incidentally fig. 4 illustrates the fact that oblique lighting picks out the boundaries of the crystalline grains, showing that these boundaries are marked by inclined surfaces connecting grains whose faces are at different levels. This is observed also in the etched surface of the metal before straining. The boundaries, which appear dark under vertical light, are bright on one side of each crystalline grain, when the light falls with grazing incidence from one side. But the sloping surfaces which mark the boundaries between the grains have by no means the sharply definite inclination which characterises the surfaces which form the slip bands. One or more groups of slip bands will shine out very brightly when the light has a particular angle of incidence, and will vanish when the incidence is slightly changed. The boundaries are not in general so bright, but they remain fairly bright while the incidence is changed through wide limits.

When the metal is much strained a second system of bands appears on some of the grains, crossing the first system at an angle, and in some cases showing little steps where the lines cross. These bands are clearly due to slips occurring in a second set of cleavage or gliding surfaces. An example of the crossed systems of bands will be seen in

fig. 8. The crystals in metals are generally cubical, but the angle at which the intersecting systems of bands cross depends on the inclination of the polished surface to the planes of cleavage. Occasionally a third system of bands may be seen.

As straining proceeds the originally smooth surface of the specimen becomes roughened by the surface grains changing in their relative levels and also becoming more or less inclined, as well as more or less stepped. All this happens in consequence of the slips which they and their neighbours undergo. To this is due the dull appearance which an originally bright surface assumes when the metal is overstrained. Under the microscope the strained surface is seen to be full of ups and downs, and a continuous alteration in focus is required to trace the system of bands, even over the face of a single grain.

When the experiment is made with a polished but unetched specimen the slip bands appear equally well. The boundaries of the grains are invisible before straining; but they can be distinguished as the strain proceeds, for the slip bands form a cross-hatching which serves to mark out the surface of each grain. To strain a polished but unetched specimen reveals in a striking way the granular character of the structure.*

Figs. 5, 6, and 7 are selected from a series of photographs showing under a magnification of 140 diameters, the same group of crystalline grains in a specimen of soft wrought iron at various stages of straining by pull. The arrows show the direction in which the pull was applied.

Fig. 5 shows the group before straining began. Fig. 6 is the same group after the strain had been carried some way past the yield point. Fig. 7 is the same group after the piece had suffered considerable further extension in the same direction. Comparison of the three will show how the grains change their shape in consequence of the slips which occur in them, and also how the faces of the grains become tilted and altered in relative level.

Fig 8 is another sample of iron strained by pull. The specimen in this case was a bar of Swedish iron, in which a comparatively large crystalline structure had been developed by annealing for some hours at 700° C. The photograph was taken after the bar had been broken in the testing machine, and shows with a magnification of 400 diameters a portion of the surface not far from the place of fracture. The large grain which appears to the left in fig. 8 measured 0·16 mm. in the direction of the arrows before straining, and was extended by the strain in that direction to about 0·2 mm. The slip bands upon it are on the average 1/400 mm. apart. This applies to both of the two systems of bands which appear in the photograph. The apparent

* The fact that the crystalline structure is revealed when a specimen with a polished unetched surface is strained has already been pointed out by Charpy ('Comptes Rendus,' vol. 123, 1896, p. 225).

width of the slip bands themselves is too small to be measured with any accuracy; it does not appear at any place here to exceed 1/2000 mm.

The slip-bands are developed by compression as well as by extension. Fig. 9 is a photograph (at 400 diameters) from the polished and etched side of a block of Low Moor iron compressed in the testing machine sufficiently to give it a considerable amount of permanent set. The bands developed by compression have apparently all the characteristics which they present in stretched pieces, and we could not, by microscopic examination of the surface, distinguish, in this respect between the effects of compression and extension. The irregular dark patches in fig. 9 are streaks of slag.

By twisting an iron bar well beyond the elastic limit the slip-bands are made to appear, for the most part in directions parallel and perpendicular to the axis of twist.

A strip of sheet metal, such as iron or copper, in the soft state, when bent and unbent in the fingers shows them well developed by the extension and compression of the surface.

We have developed the slip-bands in iron, steel, copper, silver, lead, bismuth, tin, gun-metal, and brass. In silver they show particularly well, the crystalline structure being large and the lines straight. In copper also the lines are straighter and more regularly spaced than is general in iron. Most of these metals have been tested in the form of blocks under compression. A beautiful development of slip-bands may readily be produced by pinching a button of polished silver or copper in a vice.

In carbon steels we have found the slip-bands considerably more difficult to observe than in wrought iron. The smaller granular structure of steel apparently makes the slip-bands correspondingly minute. In mild steel they are seen readily enough, but in a rather high carbon steel we succeeded in seeing them only with difficulty in the "ferrite" areas under a magnification of 1,000 diameters. A cast piece of the nearly pure iron used for dynamo magnets showed a relatively very large granular structure and well marked slip-bands.

These experiments throw what appears to us to be new light on the character of plastic strain in metals and other irregular crystalline aggregates. Plasticity is due to slip on the part of the crystals along cleavage or gliding surfaces. Each crystalline grain is deformed by numerous internal slips occurring at intervals throughout its mass. In general these slips no doubt occur in three planes, or possibly more, and the combination of the three allows the grain to accommodate itself to its envelope of neighbouring grains as the strain proceeds. The action is discontinuous: it is not a homogeneous shear but a series of finite slips, the portion of the crystal between one slip and the next behaving like a rigid solid. The process of slipping is one which takes

time, and in this respect the aggregate effect is not easily distinguishable from the deformation of a viscous liquid.

We infer from the experiments that "flow" or non-elastic deformation in metals occurs through slip within each crystalline grain of portions of the crystal on one another along surfaces of cleavage or gliding surfaces. There is no need to suppose the portions which slip to be other than perfectly elastic. The slip, when it occurs, involves the expenditure of work in an irreversible manner.

It is because the metal is an aggregate of irregular crystals that it is plastic as a whole, and is able to be deformed in any manner as a result of the slips occurring in individual crystals. Plasticity requires that each portion should be able to change its shape and its position. Each crystalline grain changes its shape through slips occurring within itself, and its position through slips occurring in other grains.*

From what is known about the break-down in elasticity which occurs as the immediate effect of overstrain and the subsequent recovery of elasticity after a period of rest, it would seem that the surfaces over which slip has occurred are at first weak, but heal with the lapse of time. To discuss these points, however, lies beyond the scope of a preliminary notice.

The experiments were made in the engineering laboratory at Cambridge, and are being continued. We wish to take this opportunity of thanking Sir W. Roberts-Austen and Mr. T. Andrews for the great kindness with which, at the outset of our work, they gave us the benefit of their experience in preparing and observing microscopic specimens of metals.

[*Note added April 14, 1899.*—In a specimen of cast nickel, which showed after etching a crystalline structure much resembling that of iron, but on a considerably smaller scale, straining developed minute slip-bands, which are clearly apparent under a power of 1,000 diameters.]

We have also examined a specimen of pure gold by compressing a cast button with a polished face, not etched. The straining reveals crystalline structure on a large scale, and in each of the crystalline grains there is a superb development of slip-bands. They are long, nearly straight, exceedingly numerous, and very closely spaced. A power of 1,000 diameters is required to see them well. Two intersecting systems are common, and three are well seen in some of the grains, forming a regular geometrical network. The intergranular boundaries are sharply defined by the meeting of the slip-bands on each grain with those on its neighbours. The slip-bands in adjacent crystals meet in a way which demonstrates the absence of any appreciable quantity of foreign matter in the intergranular junctions.]

* Attention should be called in this connection to the experiments of Messrs. McConnel and Kidd on the plasticity of glacier ice ('Roy. Soc. Proc.', vol. 44, p. 331). They found that bars cut from glacier ice, which is an aggregate of irregular crystals, are plastic.



FIG. 1.—Soft Sheet Iron strained by tension. 400 diameters.



Fig. 2. Before straining.

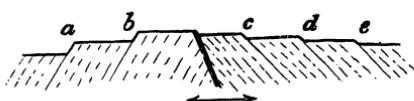


Fig. 3. After straining.



FIG. 4.—Swedish Iron, much strained, seen under oblique illumination. 280 diameters.



FIG. 5.—Before straining. 140 diameters.

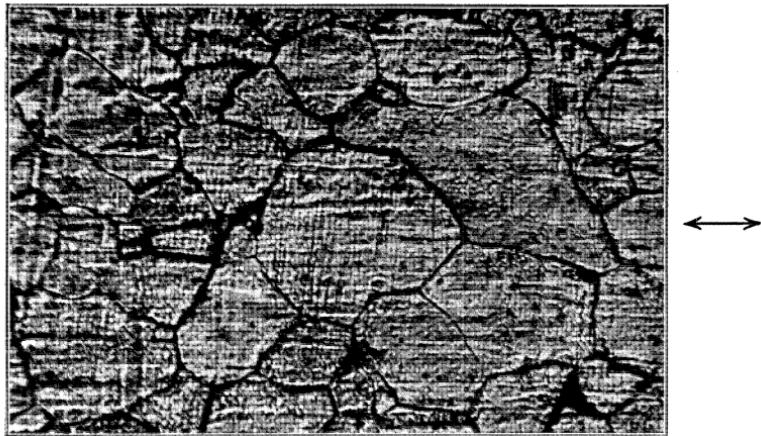


FIG. 6.—After moderate straining. 140 diameters.



FIG. 7.—After further straining. 140 diameters.

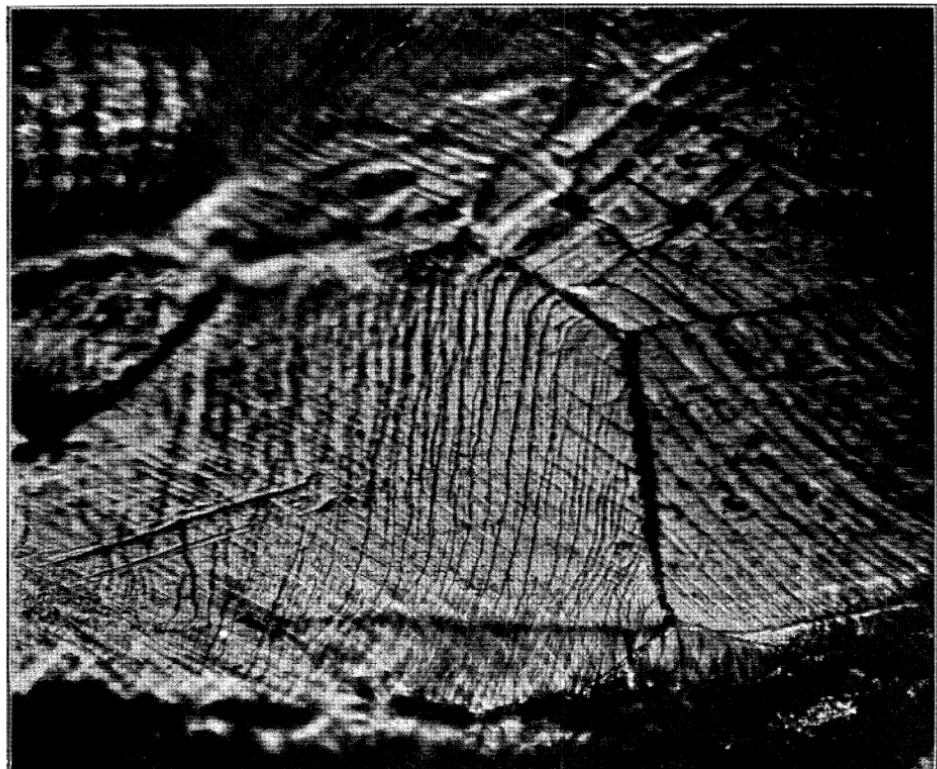


FIG. 8.—Swedish Iron, much strained. 400 diameters.



FIG. 9.—Low Moor Wrought Iron after compression. 400 diameters.

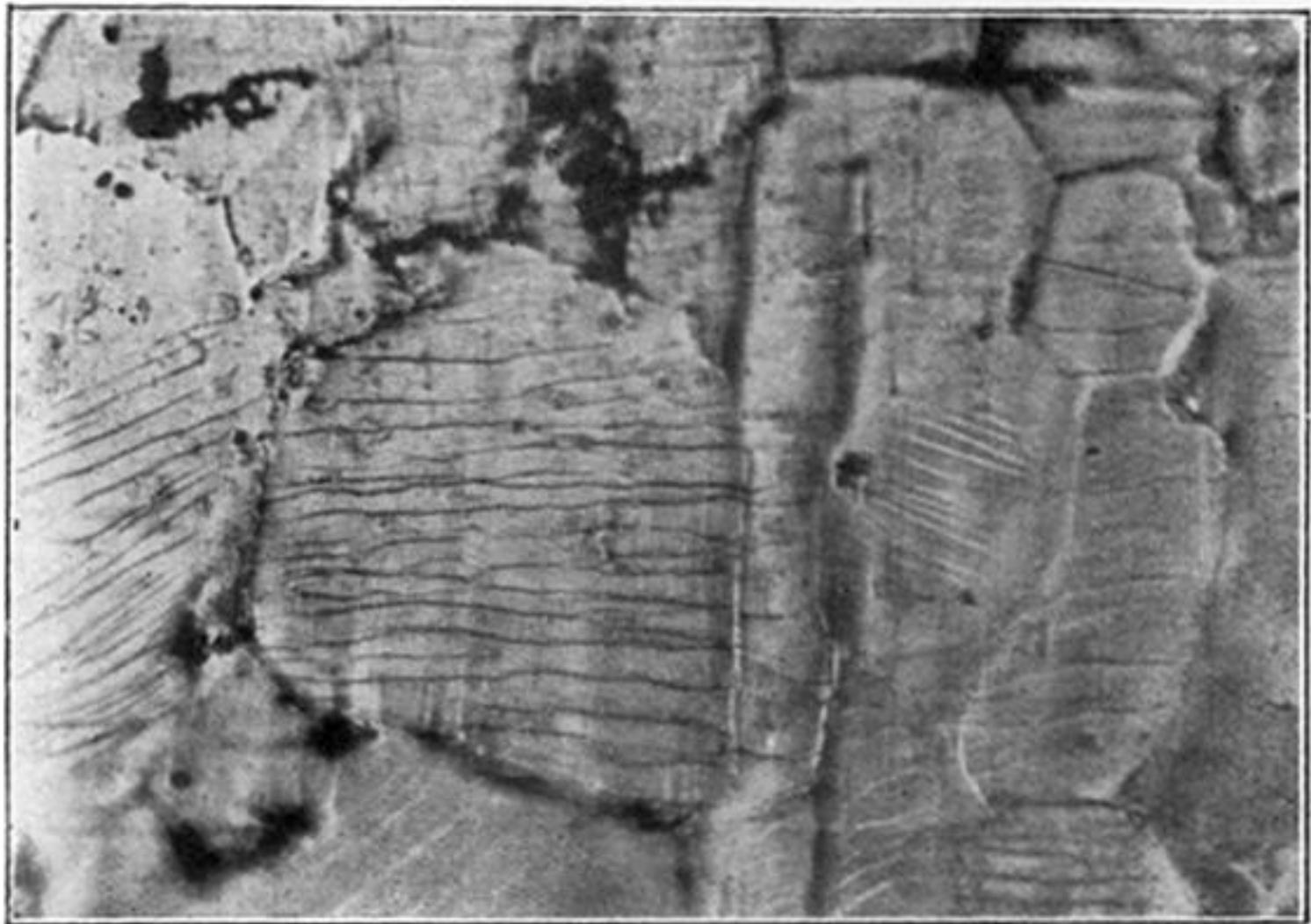


FIG. 1.—Soft Sheet Iron strained by tension. 400 diameters.

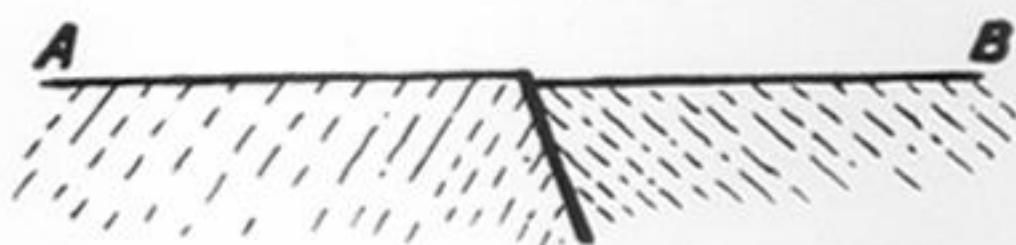


Fig. 2. Before straining.

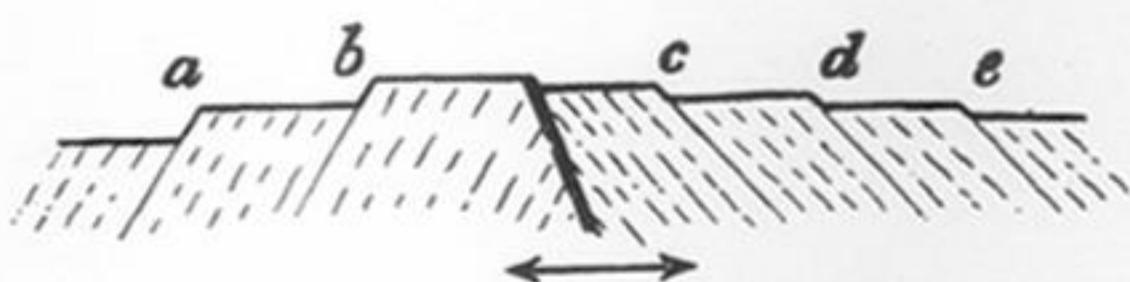


Fig. 3. After straining



FIG. 4.—Swedish Iron, much strained, seen under oblique illumination. 280 diameters.

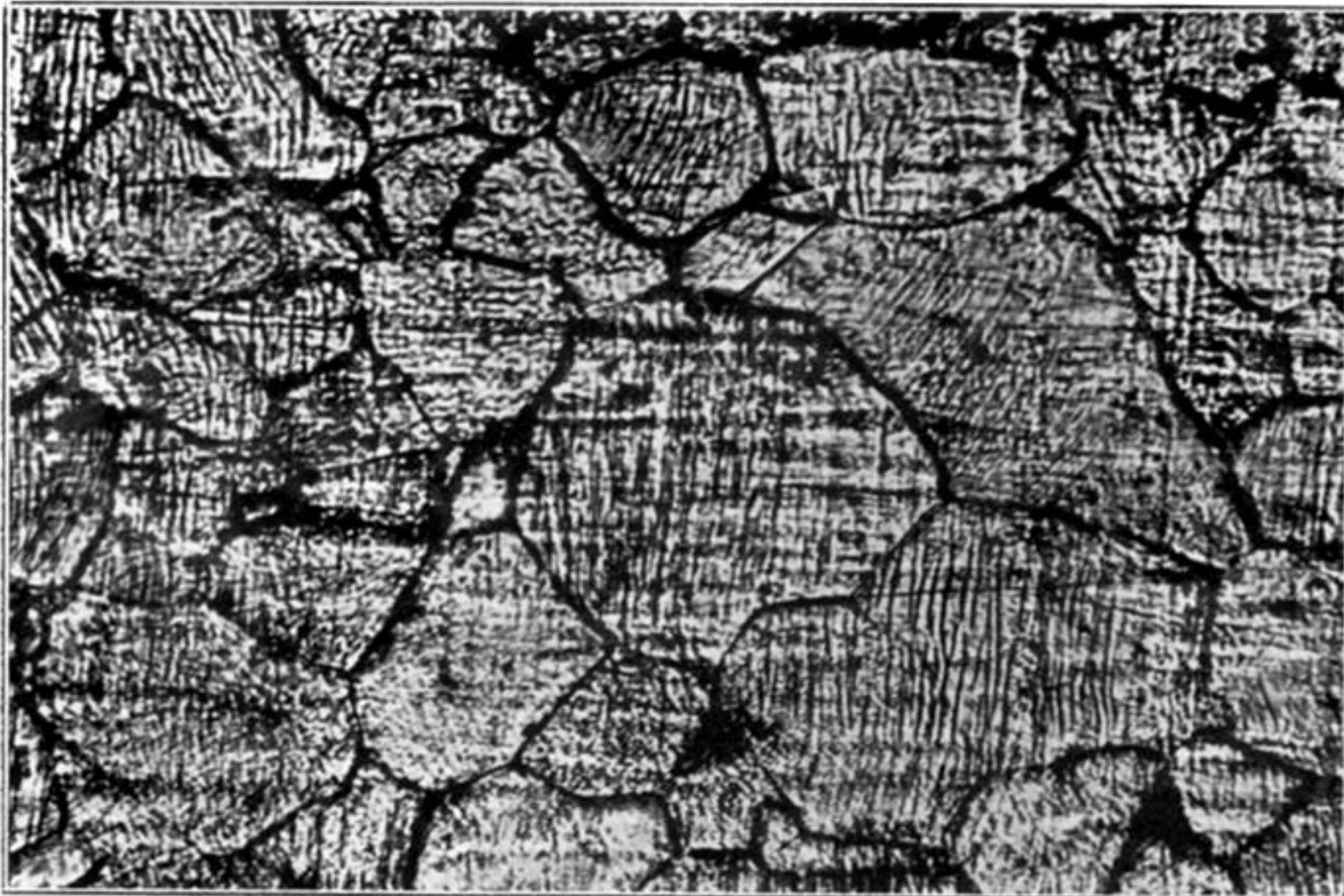


FIG. 5.—Before straining. 140 diameters.

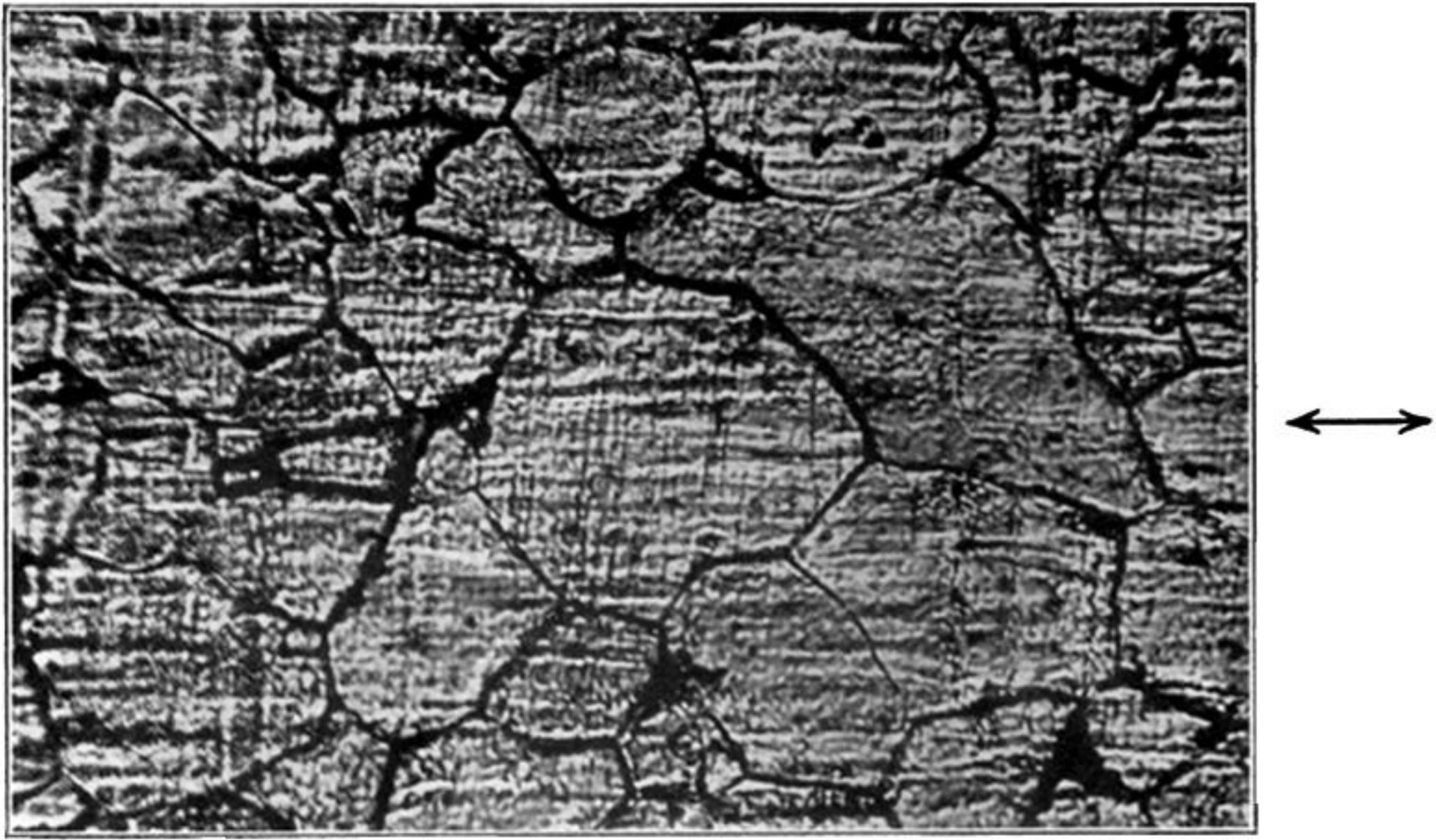


FIG. 6.—After moderate straining. 140 diameters.

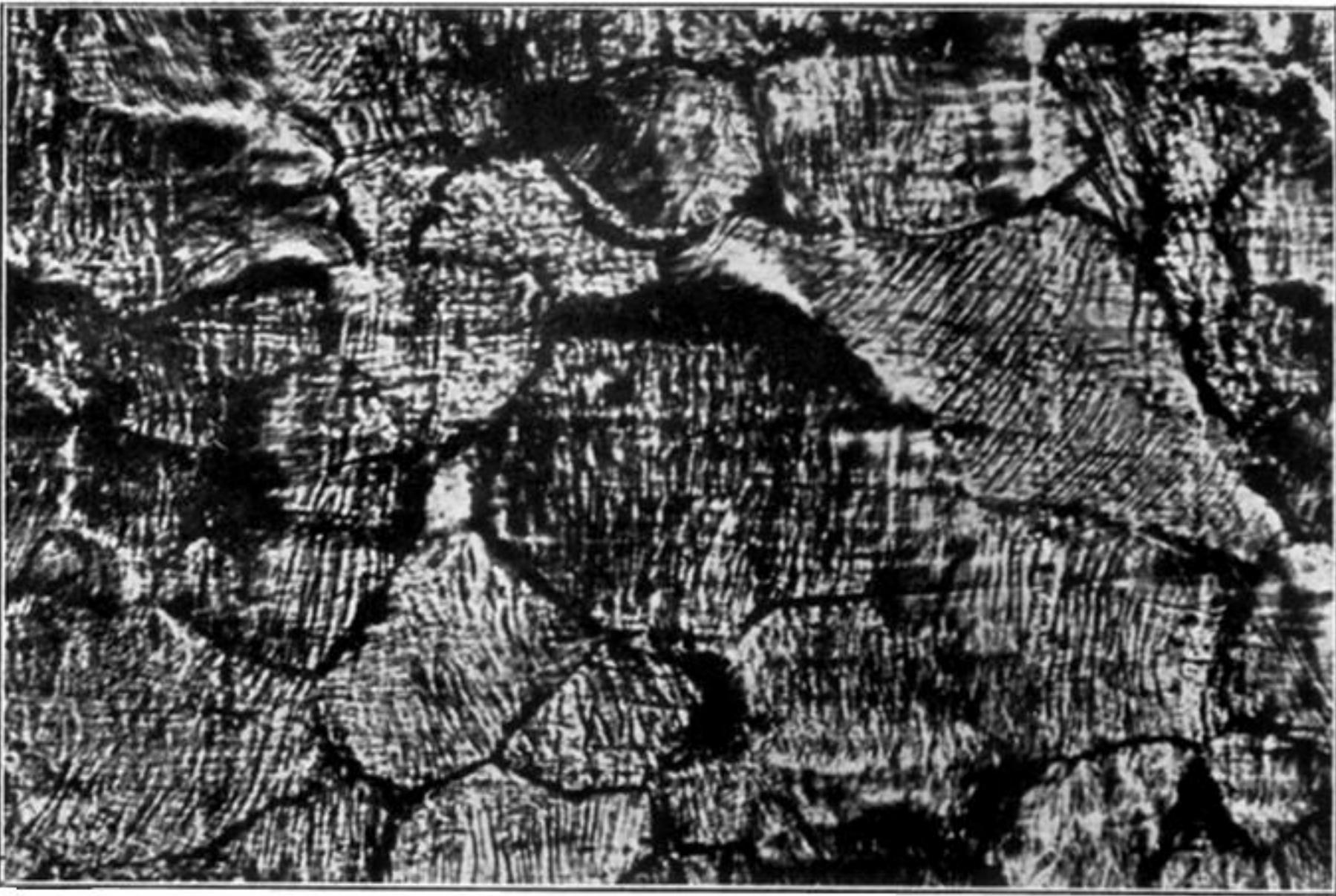


FIG. 7.—After further straining. 140 diameters.



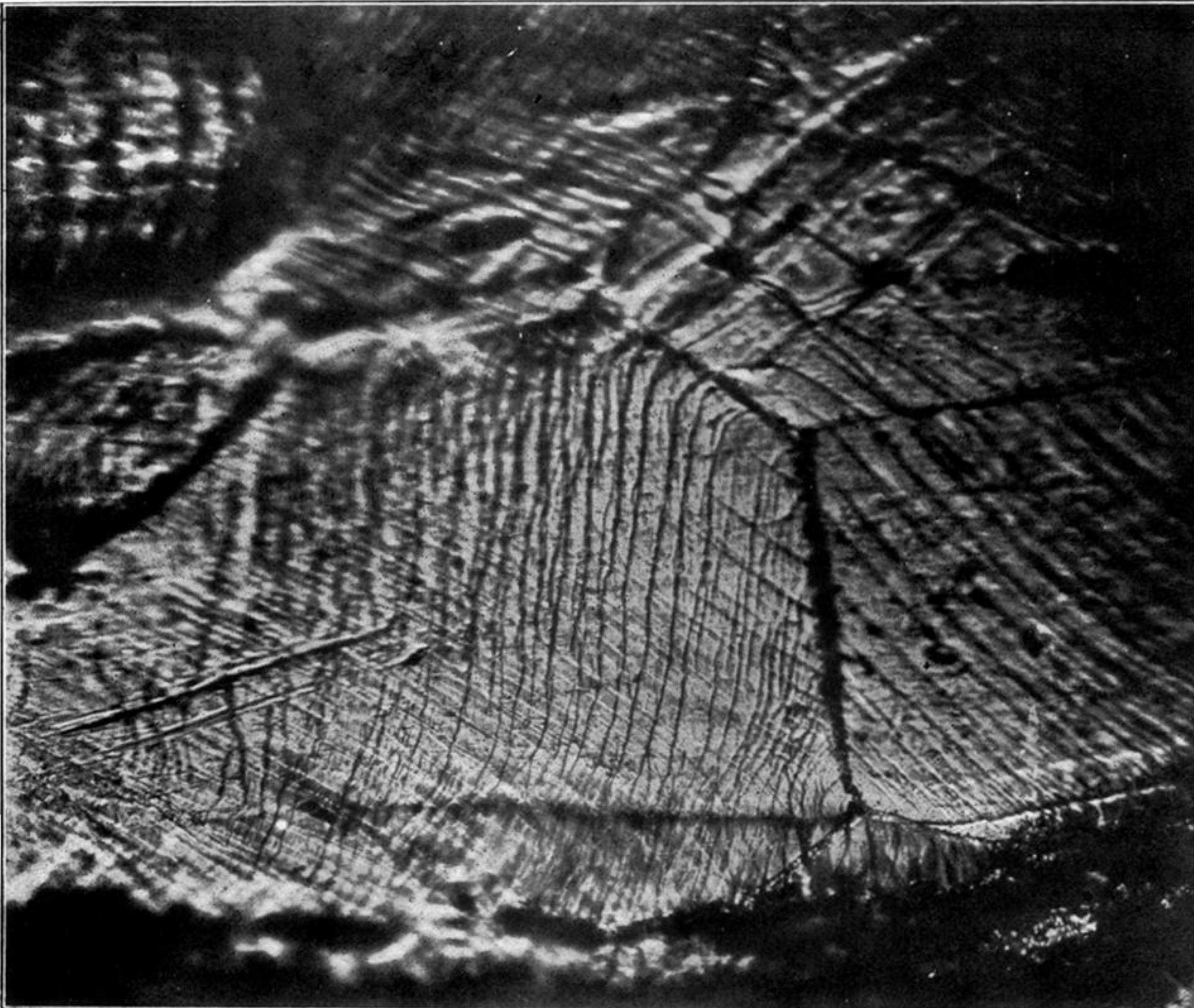


FIG. 8.—Swedish Iron, much strained. 400 diameters.

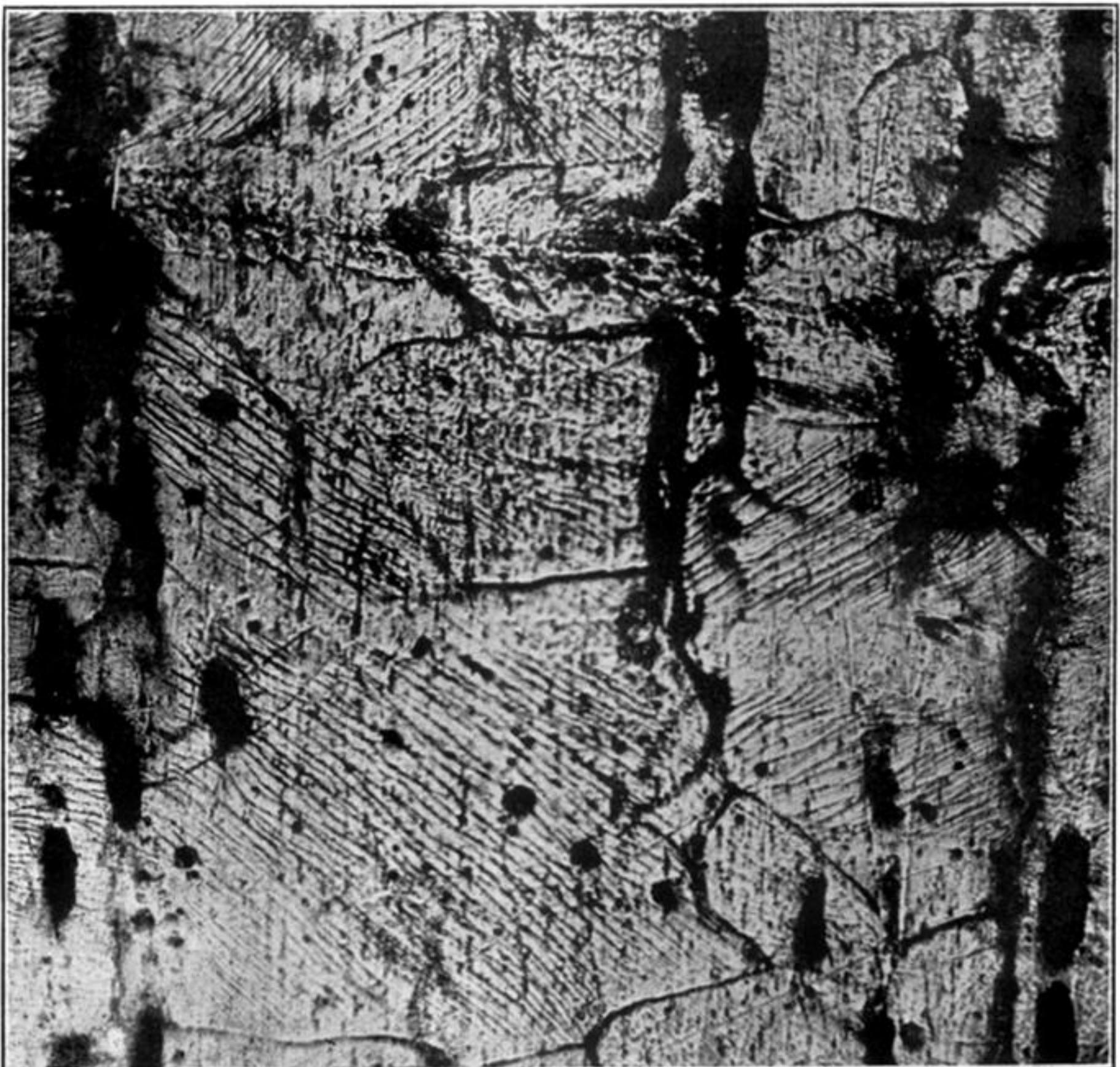


FIG. 9.--Low Moor Wrought Iron after compression. 400 diameters.